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ASTRONOMY AND ASTROPHYSICS

Lensing galaxies: light or dark?

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Abstract. In a recent paper, Hawkins (1997) argues on the basis of statistical studies of double-image gravitational lenses and lens candidates that a large population of dark lenses exists and that these outnumber galaxies with more normal mass-to-light ratios by a factor of 3:1. If correct, this is a very important result for many areas of astronomy including galaxy formation and cosmology. In this paper we discuss our new radio-selected gravitational lens sample, JVAS/CLASS, in order to test and constrain this proposition. We have obtained ground-based and HST images of all multiple-image lens systems in our sample and in 12 cases out of 12 we find the lensing galaxies in the optical and/or near infrared. Our success in finding lensing galaxies creates problems for the dark lens hypothesis. If it is to survive, ad hoc modifications seem to be necessary: only very massive galaxies ($M \gtrsim 9\times10^{11}\mathrm{M}_\odot$) can be dark, and the cutoff in mass must be sharp. Our finding of lens galaxies in all the JVAS/CLASS systems is complementary evidence which supports the conclusion of Kochanek et al. (1997) that many of the wide-separation optically-selected pairs are physically distinct quasars rather than gravitational lens systems.

Key words: Galaxies: fundamental parameters – cosmology: dark matter – gravitational lensing

1. Introduction

Gravitational lensing is an important phenomenon because it probes mass distributions of galaxies independently of their optical luminosity. In particular, it provides a unique way to search for galaxies with very high mass-to-light ratios which are otherwise difficult to detect.

In a recent paper, Hawkins (1997) performs such a search, based on published data on eight two-image gravitational lens systems and candidate lens systems with image separations $> 2''$. Statistical arguments are presented that these are indeed genuine lens systems rather than chance associations of unrelated quasars. For example, several of the quasar pairs have more similar colours than one would expect to find in the general population of quasars, and in at least one case that the spectra are so similar that when one spectrum is divided by the other, the result is a constant ratio to within the noise (Hawkins et al. 1997). No lensing galaxies are found in six of the systems, resulting in mass-to-light ratios of up to 22000 in the most extreme case. The inference is that the lensing is done by underluminous 'dark galaxies' with very substantial components of dark matter, with serious implications for cosmology as well as lensing studies. A further paper by Jimenez et al. (1997) discusses how such galaxies could be formed. However, Kochanek, Falco & Muñoz (1997) have argued against a lensing interpretation and for the hypothesis that the Hawkins lenses are binary quasar pairs, based on existing statistics of large separation lenses, because a population of wide-separation, optically-selected lenses should imply a significant, unseen, population of corresponding radio-selected lenses. They also discuss formation scenarios for such binary quasar pairs. In this paper we describe a new, well-defined, sample of gravitational lens systems selected from the JVAS/CLASS radio surveys. We discuss the search for the lensing galaxies in the 12 systems found so far and assess the implications for the proposal that dark lensing galaxies exist. In Section 2 we give a brief description of JVAS/CLASS and list the confirmed lens systems. In Section 3 we summarize the observations, both with ground-based telescopes and with the HST, in which we detect lensing galaxies in all 12 systems. Finally, in Section 4, we present our conclusions and discuss further the question of whether the optically-selected pairs (Hawkins 1997) are lens systems, physically unrelated quasar pairs or related quasar pairs.

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2. The JVAS/CLASS radio lens searches

The objective of the JVAS/CLASS surveys is to observe all northern-hemisphere sources with flux densities >30 mJy at 5 GHz, and with a radio spectral indices flatter than −0.5 ($S_\nu \propto \nu^\alpha$). The brighter section of the survey, the Jodrell Bank-VLA Astrometric Survey (JVAS) consists of the brightest ∼2400 sources ($S_{5\mathrm{GHz}} > 200$ mJy) and is described by Patnaik et al. (1992a) and Wilkinson et al. (1998) . The Cosmic Lens All Sky Survey (CLASS), which is a collaboration between groups at Jodrell Bank, Caltech, Dwingeloo and Leiden, is an extension of this work to weaker sources. The surveys used to define the JVAS/CLASS sample, and determine the radio spectral indices, are the NRAO 5-GHz surveys at the high-frequency end (Gregory & Condon 1991; Gregory et al. 1996) and either the Westerbork Northern Sky Survey (WENSS) at 325 MHz (de Bruyn et al., in preparation) or the Texas 365 MHz catalogue (Douglas et al. 1996) at the low frequency end. So far, approximately 9000 sources have already been observed of which about 8000 have been detected with 8.4 GHz flux densities $\geq$ 20 mJy.

Every effort is being made to ensure that the finished survey is complete in the sense that all gravitational lenses with image separations $< 6''$, and with image flux ratios <10 will be detected. This task is made easier by the fact that flat-spectrum radio sources have intrinsically simple structures (mostly unresolved on the arcsecond scale). Initial observations are made in snapshot mode with the VLA in A-configuration at 8.4GHz. These give 0.2 arcsec-resolution images with dynamic range $\geq$100 on the brightest component. Any object which consists of more than one component with angular separation $0\farcs3 < s < 6$ arcsec between the components is followed up by higher-resolution radio observations using some combination of the VLA, MERLIN and the VLBA. In this phase of the search for lens systems, candidates are rejected if the images have very different radio spectra, if the images have very different percentage polarizations, or if the high resolution maps reveal extended structure inconsistent with lensing (most often the putative lensed images are shown to have very different surface brightnesses). More details of the lens search procedure are given by King et al (1998a).

The radio follow-up observations of the candidates from all the sources so far observed with the VLA are virtually complete. So far we have twelve confirmed lens systems which we list in Table 1. *There are no systems that have passed all the radio tests which have been subsequently rejected by optical observations.* Hence we take as a confirmed system as one which has passed the radio tests; here we discuss the subset of these which have so far been observed with HST. There remain five recently-discovered good candidates (not included in Table 1) which still require optical follow-up observations. These five candidates have separations < 3 arcsec.

In Figure 1 we show the histogram of the maximum image separations given in Table 1 for the twelve confirmed lens systems. Our search technique is designed to pick up systems with image separations in the range 0.3 arcsec to 6 arcsec, and we believe it to be complete in this range. In particular, we have found no lens systems with separations > 3 arcsec amongst 8000 radio sources mapped. However, three systems have separations between 2 arcsec and 3 arcsec and hence lie in the separation range discussed by Hawkins.

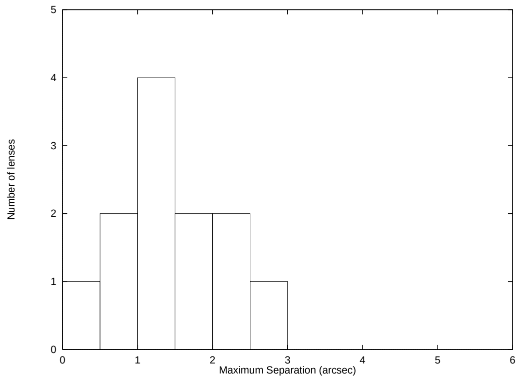

Fig. 1. Histogram of the maximum image separation (in arcsec) for the 12 confirmed JVAS/CLASS lens systems.

3. Optical and infrared follow-up; lensing galaxies

All the systems listed in Table 1 have been observed with the HST, either with WFPC2 (in V and I-bands) or with NICMOS (in H-band). Full details of the HST observations will be presented elsewhere. Figure 2 shows an example of one of the lensing galaxies detected, that of B1608+656. In all but one case the lensing galaxy has been detected in a position consistent with the gravitational lens hypothesis, the exception being B2114+022 where two galaxies are detected (Augusto et al. 1998). The resulting magnitudes are listed in Table 1. We give the magnitude within the Einstein radius except for B0218+357 and B1422+231 where values for total luminosity are taken from the literature. Multiple optical counterparts corresponding to two or more of the radio images are detected in all systems except B2114+024.

In most cases the redshifts of the lensing galaxy and the lensed object are determined and this enables us to estimate a lens mass. In the cases where the redshift information is incomplete we assume a lens redshift of 0.5 and a source redshift of 1.5. In each case we have adopted a singular isothermal sphere model for the mass distribution of the lens. The mass-to-light ratios so calculated[1] are given in Table 1, and are all consistent with the values expected if the lenses are normal luminous elliptical galaxies ($M/L_R \leq\sim 20$, e.g. Oegerle & Hoessel 1991). Both mass and light are estimated within the Einstein radius: the (non-SIS) correct mass distribution to adopt outside this radius is beyond the scope of this paper.

No K-corrections or evolutionary corrections have been applied to give the values presented in Table 1. However, these corrections are relatively unimportant in the present context as for an E galaxy at redshift 0.6 the combined value of these corrections give correction factors of $\times 0.35$, $\times 1.15$ and $\times 1.85$ in V, I, and H, respectively, for the

[1] We assume H_0=60 km s^{-1} Mpc^{-1}, Ω_0=1, λ_0=0

Table 1. Radio-loud lensed systems from JVAS/CLASS, in order of decreasing image separation. In column 2 we give the reference to the discovery paper: column 3 gives the number of images of each source component. z_s (column 4) and z_l (column 5) are the source and lens redshift. Redshifts for three systems are taken from Fassnacht & Cohen (1998) and the lens galaxy redshift for B1422+231 is from Kundić et al. (1997). The image separation (column 6) is given in arcsec. In columns 7-9, the lens magnitudes (Johnson-Cousins V, I, CIT H; typical errors ±0.2 magnitudes from measurements of different frames) and mass-to-light ratios are given. Magnitudes and inferred lens masses given are within the Einstein radius, and are from our own data, except for B1422+231 (Impey et al. 1996), B0218+357 (fits by Hjorth 1997: the magnitudes are total magnitudes rather than within the Einstein radius, making the inferred M/L ratio slightly too small), B1030+074 (Xanthopoulos et al. 1998). M/L ratios for 6 objects, plus other non-JVAS/CLASS objetcs, are given by Keeton, Kochanek & Falco (1997). The mass-to-light ratios (**bold type**) have no K- or evolution corrections (see the text for a discussion of these) and are in units of $M_\odot/L_\odot$. In column 10 we give the lens mass in units of $10^{10}M_\odot$. MG0414+054 is a rediscovery of a lens system from the MIT-Greenbank Survey. B2114+022 has 4 compact components, of which at least two are gravitational images; it is not clear if all four components are images of the same object; two galaxies are associated with the lens (Augusto et al. 1998, in preparation), as is also the case in B1127+385. References: 1. Augusto et al. 1998; 2. Hewitt et al. 1992; 3. Myers et al. 1995; 4. Fassnacht et al. 1998; 5. Xanthopoulos et al. 1998; 6. Jackson et al. 1995; 7. Patnaik et al. 1993; 8. Jackson et al. 1998; 9. Sykes et al. 1998; 10. King et al. 1997, King et al. 1998; 11. Koopmans et al. 1998; 12. Patnaik et al. 1992.

Source	Ref	No. of images	Source redshift z_s	Lens redshift z_l	Max. separ$^{n.}$	Magnitude/**M-to-L ratio** V	I	H	Mass $/10^{10}M_\odot$
B2114+022	1	2,4?	-	0.32,0.59	2.57			17.0,17.2/**2.9,1.3**	26,52
MG0414+054	2	4	2.62	-	2.09			18.2/**2.5**	24
B1608+656	3	4	1.39	0.64	2.08	21.4/**17.9**	19.0/**6.4**		52
B2045+265	4	4	1.28	0.87	1.86			19.0/**6**	86
B1030+074	5	2	1.53	0.599	1.56	22?	20.4/**7.3**		22
B1600+434	6	2	1.57	0.415	1.39	23?	21.2/**17.6**	18.5/**2.4**	12
B1422+231	7	4	3.62	0.337	1.28	21.4/**16**			12
B0712+472	8	4	1.34	0.406	1.27	22.4/**20.5**	20.0/**4.7**	17.7/**0.9**	9
B1933+507	9	10	-	0.755	1.17	<23.5/**17.2**	21.8/**7.4**	18.6/**0.6**	10
B1938+666	10	4	-	-	0.93			18.5/**0.8**	6
B1127+385	11	2	-	-	0.70	24.4,25.5/ **17.3,18.6**	22.5,23.5/ **6.2,6.1**		2.7,1.1
B0218+357	12	2	0.96	0.685	0.334	22.1/**1.3**	20.0/**0.4**		2

mass-to-light ratios (Poggianti 1997; the correction factors for spirals are not very different). It can be seen, therefore, that the corrected mass-to-light ratios for our lensing galaxies range from $\sim$1 to around 20. Of the two systems with the largest M/L, B1600+434 is an edge-on spiral (Jaunsen & Hjorth 1997; Koopmans, de Bruyn & Jackson 1998) and some internal reddening is therefore expected, which will boost the inferred mass-to-light ratio. The other high-M/L object is B2045+265, which has a large separation and contains a relatively faint (but not dark) lensing galaxy.

4. Discussion

In our radio-selected lenses, even without the detection of the lensing galaxy, there can be no doubt that one is dealing with gravitational lens systems, because of radio spectral index and radio/optical similarities of the images. The results we have obtained suggest strongly that lensing galaxies have $M/L_I \lesssim 50$ and thus are not dark. Twelve out of twelve of the JVAS/CLASS lensed systems have M/L_I ratios suggestive of normal luminous galaxies. Even if *all* the remaining 5 candidates were lensed systems, and *all* of these had no detectable lensing galaxy, this would still leave over 60% of lens systems with detected, and relatively normal, lensing galaxies compared to <25% reported by Hawkins (1997).

There is a possible explanation for the difference between our results and those of Hawkins. This is that the Hawkins sample has a fundamentally different distribution of image separations, as it contains only systems with separations greater than 2″, which, since the separation s is a function of lens mass M (e.g. Schneider et al. 1992), corresponds to relatively massive lensing galaxies ($\gtrsim 9\times10^{11}M_\odot$, see Table 1). Could only massive galaxies be dominated by dark matter?

Let us concentrate, therefore, on radio lensed systems with separation >2 arcsec. We will further restrict our consideration to those incontrovertible lens systems in which optical counterparts to the radio components have been detected. There are two such systems with separation >2 arcsec in the JVAS/CLASS sample[2]. There are two further known radio-selected systems with $s >$

[2] We do not include B2114+024 as there is no detection of optical counterparts to any of the radio images.

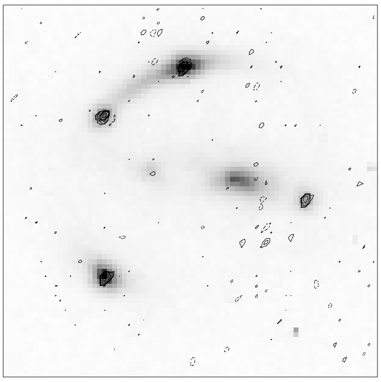

Fig. 2. The MERLIN 5-GHz image (contours) of B1608+656 (made from a 12-hour track on 1996 January 29; noise level of 130μJy/beam; contours are at 300μJy/beam$\times[-1,1,2,4,8,16,32]$) superimposed on the HST/WFPC2/814-nm image (greyscale) of B1608+656. The lensing galaxy is clearly visible in the optical image, as are lensed arcs due to the extension of the lensed image, which is a post-starburst galaxy (Fassnacht et al. 1996).

$2''$; B0957+561 (from Hawkins' sample) and B2016+12 (Lawrence et al. 1984). In all four of these normal (not dark) lensing galaxies are detected. Thus amongst *confirmed* lens systems with separations $> 2''$ there is no evidence for dark lenses.

There is no reason why any bias should be introduced by the use of radio selected systems; it is simply a way of securely identifying lens systems without the necessity of identifying a lensing galaxy. The discrepancy between the results for radio-selected lens systems, even for large separation lenses, and the mostly optically-selected sample of Hawkins (1997) is therefore puzzling.

We note, however, that Hawkins only considers systems with 2 images. Among the radio-selected systems there are many 4-image systems. Could the dark lenses be found only in the 2-image systems? Kochanek et al. (1997) pointed out that in general, one would expect a greater preponderance of 4-image systems where the lensing mass distribution, particularly the halo, is more elliptical (e.g. King & Browne 1996), and that one might therefore postulate that 'dark lenses' have spherically symmetric mass distributions. This, however, fails to account (Kochanek et al. 1997) for why the existing radio-selected two-image systems do not have dark lenses, as well as for why we find no two-image systems with dark lenses in JVAS/CLASS.

In summary, there are two conditions that must be met in order to reconcile our observations with the idea of dark lenses. First, in order for us to find no dark lenses in the JVAS/CLASS sample, there must be a sharp cutoff such that all dark lenses must have masses of $\gtrsim 9 \times 10^{11} M_{\odot}$. Second, in order to explain the detection of lenses in the radio lens systems with separations >2 arcsec (mostly quads), dark lenses should have much rounder mass distributions than the luminous lenses (Kochanek et al. 1997). The alternative to these two conditions is to suppose that most, or even all, of the systems discussed by Hawkins in which no lensing galaxy is found, are indeed not lens systems. This is despite the fact that in each individual case we find the arguments persuasive that the quasar pairs are not random associations. However, if there are no dark lenses, the frequency of close physically associated pairs of quasars has hitherto been greatly underestimated.

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